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**VERSION WITH MARKINGS**  
**TO SHOW CHANGES MADE**  
**TO SPECIFICATION**



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**TITLE: IMPROVED ELECTROMAGNETIC WORK COIL**

This is a utility patent application which claims benefit of U.S. Provisional Application No. 60/398,982 filed on July 25, 2002.

**BACKGROUND OF THE INVENTION**

1. Field of the Invention:

This invention is directed to electromagnetic work coils for electromagnetic force machines that produce a pulling (tension) force on a conductive material, which may be used for metal forming, removing dents, or performing nondestructive proof load tests.

2. Description of the Related Art:

In the past, a variety of electromagnetic force (EMF) pulling machines and electromagnetic coils have been developed for use in the production and maintenance of conductive panel work pieces to perform nondestructive tests on panel bonds and to remove

1 dents.

2 U.S. Pat. No. 4,148,091, issued to Karl A. Hansen et al. on April 3, 1979 entitled  
3 "Electromagnetic force machine with universal portable power supply," and U.S. Pat. No.  
4 3,825,819, issued to Karl A. Hansen et al on July 23, 1974 entitled "Dynamic Proof Loading  
5 of Metal Bond Structures Using Pulsed Magnetic Fields," describe such a machine. U.S. Pat.  
6 No. 5,046,345, issued to Peter B. Zieve on September 10, 1991 entitled "Power Supply for  
7 Electromagnetic Proof Load Tester and Dent Remover," describes a power supply for such a  
8 machine. U.S. Pat. No. 4,986,102, issued to I. Glen Hendrickson et al. on Jan. 22, 1991  
9 entitled "Electromagnetic dent remover with tapped work coil," describes another power  
10 supply and electromagnetic coil for such a machine.

11 U.S. Pat. No. 4,061,007, issued to Karl A. Hansen et al. on Dec. 6, 1977 entitled  
12 "Electromagnetic dent remover with electromagnetic localized work coil," and U.S. Pat. No.  
13 4,127,933, issued to Karl A. Hansen et al. on Dec. 5, 1978 entitled "Method of making work  
14 coil for an electromagnetic dent remover," describe several electromagnetic coils for use with  
15 such a machine and the methods used to manufacture them. U.S. Pat. No. 4,116,031, issued  
16 to Karl A. Hansen et al. on Sep. 26, 1978 entitled "Flux concentrator for electromagnetic  
17 pulling," describes another electromagnetic coil for such a machine that utilizes a secondary  
18 coil and is referred to as a flux concentrator.

19 U.S. Pat. No 5,575,165, issued to Thomas J. Roseberry on Nov. 19, 1996 entitled  
20 "Method of dent removal using a resonance damping vacuum blanket," describes a vacuum  
21 system for stiffening the panel work piece for use with such a machine and electromagnetic  
22 coil.

23 The electromagnetic work coils for electromagnetic force (EMF) pulling machines

1 create a pulling (tension) force on conductive material by first presenting a slowly increasing  
2 tangential magnetic field that penetrates into a conductive panel work piece. It is a  
3 requirement that the magnetic field be presented slowly enough so the skin depth of eddy  
4 currents reacting in the work piece is greater than the material thickness. This minimizes the  
5 reacting Lorentz force so that the work coil and conductive panel work piece do not push  
6 away from each other. Next, the work coil quickly must collapse the magnetic field from the  
7 face of the work piece. The collapse must be sufficiently rapid enough such that the skin  
8 depth of reacting eddy currents is less than the panel work piece thickness. The reacting eddy  
9 currents in the presence of the magnetic field cause a Lorentz force that is oriented normal to  
10 both and draws the work piece and the work coil together. This pulling force, or tension  
11 force, may be used for nondestructive pulling tests or to pull a dent out of the work piece.

12 The physical requirements of the work coil for an EMF pulling machine are different  
13 than a coil or device used with an EMF machine that pushes. In a typical EMF machine that  
14 pushes, a repulsive force is used to compact, swage, or rapidly move a conductive part away  
15 from the work coil. Since the force on the work coil is in the opposite direction, the design  
16 for a pushing work coil is significantly different. The coil windings can be backed and  
17 supported directly to withstand the pushing forces. For the pulling work coil the windings  
18 must withstand a pulling force. The windings must slowly present the magnetic field with a  
19 significant current density. This results in a greater amount of energy dissipated in the work  
20 coil in the form of heat that must be dissipated to maintain conductance and material strength.

21 While prior art work coils have proven to be satisfactory for some work,  
22 improvements are desired. It is desired to pull dents from thicker, harder, or less conductive  
23 materials like titanium. It is further desired to pull higher aspect ratio dents with greater

1 plastic deformation. This requires a coil that can withstand greater thermal and mechanical  
2 stress. As the panel work piece material increases in thickness, the presentation of the  
3 magnetic field has to be slower to prevent pushing the panel work piece and work coil away  
4 from each other. This requires increased energy from the EMF power supply that will be  
5 converted to heat in the electrical resistance of the coil windings. The work coil must be  
6 cooled or capable of dissipating the extra heat. Additionally, for a thicker panel work piece,  
7 it is desirable to increase the magnetic field strength to create higher pressure necessary to  
8 perform work on the material. The increased magnetic field requires an increased current  
9 density and will impart additional mechanical and thermal stress on the coil windings. We  
10 desire to do work to the work piece without doing work on the coil so that the coil can be  
11 reused and jobs accomplished safely. At the energy levels of interest, some prior art coils  
12 have failed destructively, ejecting molten copper.

13 As the panel work piece thickness is increased, a repulsive force increases due to the  
14 imperfect slow field presentation that will reduce the effectiveness of the process. This force  
15 may be minimized by slowing down the field presentation or it can be counteracted by  
16 preloading or pushing the work coil into the work piece. If the preloaded force is overcome,  
17 the gun and panel work piece separation velocity can be minimized with a heavier gun and  
18 more rigidly backed panel work piece.

19 Another method used in the prior art to improve performance with thicker panels is to  
20 apply a vacuum between the work coil and the panel work piece. This is attractive because it  
21 provides atmospheric pressure applied evenly and directly behind the panel work piece  
22 material and behind the work coil. This technique should not be confused with the concept  
23 taught in U.S. Pat. No 5,575,165 where a vacuum blanket is used to stiffen a thin aluminum

1 panel work piece around the area to be pulled to dampen any resonance. The performance of  
2 preloading is an improvement in some cases whether it is applied by the operator pushing or  
3 by an applied vacuum.

## 4 5 **SUMMARY OF THE INVENTION**

6 Accordingly, it is an object of this invention to provide an improved electromagnetic  
7 work coil to use with electromagnetic force machines that produces a pulling (tension) force  
8 on a conductive work piece.

9 It is a further object of this invention to provide an electromagnetic work coil with a  
10 longer lifetime.

11 It is a further object of this invention to provide an electromagnetic work coil that can  
12 create a larger and stronger magnetic field that is tangential to the work piece.

13 It is a further object of this invention to provide an electromagnetic work coil that can  
14 provide a slower presentation of the magnetic field to provide penetration into thicker work  
15 pieces.

16 It is a further object of this invention to provide an electromagnetic work coil that is  
17 more efficient with the use of energy to minimize the size and weight of the power supply  
18 necessary to power the electromagnetic work coil.

19 It is a further object of this invention to provide an electromagnetic work coil that  
20 improves the performance when operator or vacuum preload is applied.

21 These and other objects are met by the invention disclosed herein that improves the  
22 performance and efficiency of the work coil used with an electromagnetic pulling machine.

23 As taught in U.S. Patent No. 4,148,091, the present invention has a stressing region where the

1 electric current through conductive windings of the work coil creates a tangential magnetic  
2 field that is concentrated on a work surface. The stressing region is composed of multiple  
3 windings of conductors that are insulated from each other. The present invention improves  
4 the mechanical strength of this stressing region by providing a clamp around the windings of  
5 the stressing region to place the windings in compression in the axis of the tangential  
6 magnetic field. This compression has a couple of advantages. It isolates the windings in the  
7 area leading to the stressing region from tangential forces that are imparted on the windings  
8 in the stressing region. It also compresses the insulation between the windings to evenly  
9 counteract the tangential forces and prevent movement of windings. With the cylindrical  
10 coils described in U.S. Pat. No. 4,148,091, the tangential forces were partly counteracted by  
11 the winding area leading to the stressing region and resulted in stretched, buckled, and  
12 displaced windings. The compression applied by the clamp helps isolate and prevent this.  
13 The clamp also allows thinner insulation to be used between windings.

14 Minimizing the area taken up by insulation in the stressing region allows a higher  
15 winding density, which is desired to decrease the electric current necessary to create the large  
16 magnetic field. While such clamping may benefit any electromagnetic coil, the clamp of the  
17 present invention especially benefits the application for electromagnetic dent removal where  
18 the panel work piece is pulled into and formed by the work coil. To accomplish this, a  
19 counteracting pushing force from the clamp material surrounding the stressing region needs  
20 to be translated through the insulation layers to the windings that are performing the pulling.  
21 The clamp improves the integrity of the stressing region to translate this force. Additionally  
22 the clamp can be tapered to trap the windings and further help translate the force for pulling  
23 dents.



1           The embodiments of the present invention also provide winding path and  
2           corresponding magnetic field geometry improvements. The cylindrical coils taught by U.S.  
3           Pat. No. 4,148,091 have a crescent shaped pulling area in an arc with the windings around the  
4           center of the coil. A disadvantage of this geometry is that the magnetic field extending  
5           normal to the panel work piece is concentrated higher in the center of the coil. As a result the  
6           field is drawn inside the copper windings of the stressing region. This causes excessive  
7           tangential forces on those windings that are not evenly balanced by corresponding forces in  
8           adjacent windings. The embodiments of the present invention take advantage of other return  
9           paths for windings symmetrically around the linear stressing region. The complete set of  
10          possible return paths of the windings can be visualized by cutting a toroid in half where the  
11          cut face is adjacent the panel work piece. Rather than a cylindrical coil, it is beneficial to  
12          have the return path of windings symmetric and spread out around the stressing region. This  
13          is beneficial for multiple reasons. By providing symmetric arc paths around the stressing  
14          region, the normal and internal magnetic fields that do not contribute to the desired work are  
15          minimized. This decreases the magnitude of the tangential forces on the windings that have  
16          limited the prior art designs. The tangential forces that remain are then balanced by opposing  
17          windings within a linear stressing region due to the symmetry of the magnetic field. This  
18          optimized symmetric magnetic field further isolates the stressing region tangentially from the  
19          surrounding area.

20          Spreading out the return path windings around the stressing region results in a lower  
21          inductance coil that is more efficient. As the inductance of the coil is decreased without  
22          sacrificing the pulling performance, the power supply for energizing the present invention can  
23          take advantage of this efficiency and be designed lighter and smaller. Efficiency of the

1 present invention is also provided as every winding in the stressing region gets to contribute  
2 to the magnetic field. With the prior art cylindrical coil a number of windings near the center  
3 of the coil in the stressing region had to be diminished with lower current concentration to  
4 strengthen the winding and reduce the force from the large central magnetic field.

5         Spreading out the return path windings has several other important advantages. If the  
6 coil is made from a precut ribbon of copper as described in U.S. Pat. No. 4,127,933, a  
7 difficulty of making the coil is that the diameter, insulation, and copper thickness has to be  
8 perfect to line up the precut features added to the copper windings. With the present  
9 invention, the windings can also be manufactured from precut copper but the alignment is  
10 only important through the stressing region. Any slack or tolerance variation can be taken up  
11 outside of it. Another advantage of spreading out the windings is that the electric isolation  
12 from winding to winding only becomes critical near and inside the stressing region. Outside  
13 the stressing region distances can be increased with extra and more economic insulation  
14 material. Finally, the advantage of the spread out windings is that conductive windings  
15 themselves act as thermal conduits of heat, transferring the heat away from the stressing  
16 region. Spreading out the windings provides greater heat capacity and greater available  
17 surface area to dissipate the heat. With increased winding thickness or winding spacing,  
18 cooling holes can be tolerated outside of the stressing region for forced air or other cooling  
19 means.

20         With a symmetric return path of windings around the coil, the stressing region is now  
21 located at the center of the coil. This too has several advantages. In the prior art, the  
22 stressing region was offset to one side of the coil. With the stressing region located at the  
23 center of the work coil, the forces that are not cancelled at the stressing region are normal to

1 the panel work piece and presented without a large moment to the mass of the coil and to the  
2 gun in which the coil is mounted. This makes it easier for the operator to apply a preload.  
3 When the surface area around the stressing region is equal, a vacuum is applied between the  
4 coil and the panel work piece to provide a preload, it does not present a mechanical moment  
5 on the coil. For the cylindrical work coil with a stressing region offsets to one side, the  
6 resulting moment has to be counteracted. Another benefit of a centrally located stressing  
7 region is that the high electromagnetic field that is generated is inherently better shielded.  
8 The copper windings surrounding the stressing region help confine the magnetic field  
9 externally without extra shielding. A conductive shell around the coil can further help  
10 confine the EM pulse.

11 Further improvements to work coil geometry are disclosed in embodiments for  
12 application to shaped panel work pieces. Many conductive panel work pieces, on which an  
13 electromagnetic dent remover is used, are functionally in a convex shape, such as the leading  
14 edge of an airplane wing or the surface of an aerodynamic fuselage. The winding current  
15 path leading to the stressing region can take advantage of this geometry by more closely  
16 following the convex contour of the panel work piece. This can enhance the tangential  
17 magnetic field in the pulling surface area. In other applications, the panel work piece is in a  
18 concave shape such as the inside of a jet engine inlet. In this case it is beneficial to conform  
19 to the concave shape so that the central stressing region is in mechanical proximity to the  
20 panel work piece. To match the concave shape, rather than making the winding current path  
21 follow the concave contour and thus degrade the presented magnetic field, the coil is rotated  
22 ninety degrees and the necessary profile cut in the orthogonal axis.

1           A couple of manufacturing methods can be utilized and the inherent attributes of  
2 those methods will allow coils of varying capabilities and features to be produced. The  
3 simplest embodiment is made from a long strip of copper that is precut in 2D by water-jet or  
4 punched with the desired features and then wound and insulated. One benefit of this  
5 approach is the ability to stack windings both horizontally and vertically. Another method is  
6 to cut the same copper strip in 3D with a CNC to additionally allow variable thickness of the  
7 windings. Varying the thickness of the windings can be beneficial as the area outside of the  
8 stressing region can be made thicker to provide extra strength, lower current density, less  
9 resistance, and greater thermal conductivity. The area leading to the stressing region can be  
10 tapered and narrowed to provide the higher current density in the stressing region. Another  
11 embodiment accomplishes the same using the 2D cut strip of copper by winding it around  
12 precut pieces of a conductive material like aluminum or copper. Another embodiment can  
13 utilize advantages afforded by wire EDM. Rather than bending copper into windings, a solid  
14 conductive material like copper can be milled and then cut by wire EDM so the geometry of  
15 each winding is varied continuously. With the wire EDM the winding thickness can be  
16 increased dramatically outside of the stressing region in a tapered and controlled fashion.  
17 This has advantages for providing strength and heat capacity outside of the stressing region  
18 but is also presently a more expensive method of manufacture.

19           The materials used for making a work coil of the present invention are also varied.  
20 The conductor material is desired to be as conductive as possible to minimize resistance.  
21 This is especially important for electromagnetic metal forming that pulls instead of pushes  
22 because the necessary slow presentation of the magnetic field can locally dissipate a lot of  
23 heat. Cooling a number of materials like copper can further minimize resistance. However

1 the strength of the windings in the stressing region is important since it is a primary  
2 mechanical working element to produce forming stresses in the panel work piece. A material  
3 like aluminum dispersion strengthened copper is attractive as it extends the annealing  
4 temperature and strengthens the copper while minimally degrading the electrical and thermal  
5 conductivity.

6 An embodiment of the present invention further strengthens the windings in the  
7 stressing region by using a bonded metal for strength. A higher conductivity material such as  
8 copper can be explosively bonded to a lower conductivity material such as titanium or  
9 stainless steel. Both materials compose a winding. This technique allows higher current  
10 densities in a smaller copper region while maintaining the geometric and even extra material  
11 strength of the windings. The magnetic field is drawn into the copper some by a percentage  
12 of cross sectional current flowing in the secondary material, which can be beneficial as the  
13 force on the copper is away from the panel work piece.

14 In prior art, the copper was spirally wound with Kevlar and vacuum impregnated with  
15 an epoxy. In the present invention the Kevlar or fiberglass can be draped over the windings  
16 to provide structural integrity and support for the windings in the stressing region. To  
17 maintain dielectric integrity it is best if the material for insulating the windings in the  
18 stressing region is solid with a controlled thickness. A material like polyimide film is  
19 attractive because of its excellent dielectric strength and capability to withstand heat. Other  
20 materials and methods of insulation exist. It is important to realize the critical dielectric  
21 insulation strength is the insulation between the coil and the conductive panel work piece.  
22 The insulation requirement between windings is generally less. The clamp material near the  
23 stressing region could be a strong insulating material like G-10. A fairly lower conductivity

1 and low permeability material such as titanium or stainless steel can be used in proximity of  
2 the stressing region, such as bolts for the clamp. A high permeability ferromagnetic material  
3 will magnetically saturate and fight the rapidly collapsing field that is desired.

4 If the temperature of the coil is decreased the resistance of the windings of the coil is  
5 decreased. While we may wish to even try a super-conducting coil, typically the thermal  
6 mass and heat conductivity of the panel work piece is significant and the coil windings are  
7 too close of a proximity to the panel work piece. Usually the described machines are used on  
8 skin panels that are mounted on an airplane or other part when there is no access to the back  
9 of the panel work piece. However, cooling of the work coil prior and during use can be  
10 beneficial. With the symmetric clamp of the present invention, cooling holes in the clamp  
11 can be aimed over the pulling area to form a dry air curtain and help prevent ice buildup  
12 during use.

#### 13 DESCRIPTION OF THE DRAWINGS

14 Fig. 1 is a perspective view of a work coil mounted in an electromagnetic dent  
15 remover gun, adjacent a dented panel work piece.

16 Fig. 2A is a perspective view of a cylindrical electromagnetic coil found in the prior  
17 art.

18 Fig. 2B is a perspective view of the coil shown in Fig. 1 showing the conductor  
19 windings in the coil.

20 Fig. 2C is a top plan view of the work surface of the coil shown in Fig. 2A.

21 Fig. 2D is a sectional side elevation view of the coil shown along line D-D in Fig. 2C.

22 Fig. 3A is a perspective view of the improved work coil disclosed herein with a  
23 clamped linear stressing region.

1 Fig. 3B is a perspective view of the conductor windings and clamp of the coil shown  
2 in Fig. 3A.

3 Fig. 3C is a top plan view of the work surface of the coil shown in Fig. 3A.

4 Fig. 3D is a side elevation view of the conductor windings and clamp of the coil  
5 shown in Fig. 3A.

6 Fig. 4A is a perspective view of a work coil with symmetric windings and clamped  
7 linear stressing region.

8 Fig. 4B is a top plan view of the work surface of the coil shown in Fig. 4A.

9 Fig. 4C is a side elevation view of the clamp and half the conductor windings of the  
10 coil shown in Fig. 4A.

11 Fig. 5 is an illustration of the work surface of a coil with higher current density and  
12 tapered conductor windings.

13 Fig. 6A is a cross-sectional view of conductor windings in a clamped stressing region.

14 Fig. 6B is a cross-sectional view of conductor windings strengthened with a  
15 secondary metal in the clamped stressing region.

#### 16 17 **DESCRIPTION OF THE PREFERRED EMBODIMENT(S)**

18 Fig. 1 shows a perspective view of a preferred embodiment electromagnetic work  
19 coil, generally referenced as 10, mounted in an example electromagnetic pulling gun 91 and  
20 positioned adjacent a conductive panel work piece 90. An electromagnetic pulling gun 91  
21 with work coil 10 is powered by an electromagnetic pulling power supply (not shown)  
22 capable of providing a slowly rising current followed by a rapid opposing current. When  
23 energized by an electromagnetic pulling power supply, the work coil 10 imparts a pulling or

1 tension force in the panel work piece 90. A pulling or tension force may be used to pull dents  
2 out of the work piece 90. When used to pull dents, the electromagnetic pulling gun 91 has  
3 been commonly referred to as an electromagnetic dent puller or an electromagnetic dent  
4 remover.

5 Figs. 2A - 2D shows a prior art cylindrical electromagnetic work coil, generally  
6 referenced as 70. The cylindrical electromagnetic coil 70 is composed of conductive coil  
7 windings 71, spirally wrapped with Kevlar or fiberglass fabric, and wound around a center  
8 dielectric core 72. The coil windings 71 are potted or encapsulated within insulating shell 73.  
9 The coil terminals 84 provide conductive mating surfaces to interface with the pulling gun  
10 91. The geometry of the coil windings 71 defines the shape of the magnetic field and  
11 provides mechanical strength, so they largely define the performance of cylindrical  
12 electromagnetic coil 70.

13 The coil windings 71 contain pre-punched tapered apertures 85 and machined slots 87  
14 and 88 to guide the current in a specific path. The slots 87 and 88 are machined after the coil  
15 70 is wound and potted. As shown in Fig. 2C, the coil windings 71 comprise the central  
16 stressing region 80, two lead-in winding regions 81, 81', and the return path winding region  
17 82. The stressing region 80 is the region of the coil 70 that can pull dents and has the highest  
18 magnetic field due to apertures 85 and slot 87 which route the energizing current into the  
19 highest density. The lead-in winding regions 81, 81' has a tapered magnetic field that  
20 decreases as the aperture 85 tapers and provides additional conductive cross sectional area.  
21 In the return path winding region 82, the current is routed away from the panel work piece 90  
22 by slot 88.

23 Fig. 2D shows more clearly the locations of the stressing region 80 and the return path



1 winding region 82. With an energized current into the page through stressing region 80, the  
2 magnetic field 150 is represented with the clockwise vectors around stressing region 80.  
3 With an energized current out of the page through the return path winding region 82, the  
4 magnetic field 152 is represented with the counterclockwise arrows around the return path  
5 winding region 82. Since the same current must flow through both regions 80, 82 the  
6 magnetic field 150 is stronger around the denser windings in stressing region 80.

7         Despite the complex winding geometry of prior art cylindrical coil 70, there is always  
8 a strong magnetic field vector through the middle of a cylindrical coil 70 due to a consistent  
9 winding path around the center dielectric core 72. To help compensate this central vector the  
10 inside windings of stressing region 80 are increased in height with successively smaller  
11 apertures 85 and a limited depth on machined slot 87. This helps taper the current density of  
12 the inside coil windings 71 and reduces tangential Lorentz forces.

13         The strong monopole of the cylindrical coil 70 forces the magnetic field 150 into the  
14 inside windings of stressing region 80 and the inside windings of return path winding region  
15 82 as shown. This creates increased Lorentz force and voltage stress on the inside coil  
16 windings 71. The Lorentz force is normal to the energizing current and normal to the  
17 resultant magnetic field, so it is tangential with the working surface of the coil 70. The  
18 tangential force and voltage stress between coil windings 71 on the inside edge in the  
19 stressing region 80 is a cause of failure in these prior art cylindrical coils 70. Often the  
20 winding material becomes stretched over successive operations because the coil windings 71  
21 in the stressing region 80 do not have the strength to withstand tangential forces. The  
22 dielectric potting or encapsulation does not provide sufficient restraint and dielectric through  
23 heat and use.

1           The embodiment of the present invention shown in Fig. 3A is an improved cylindrical  
2 electromagnetic work coil, generally referenced as 50. The improved cylindrical coil 50  
3 comprises similar components to cylindrical coil 70 with conductive coil windings 51 spirally  
4 wrapped with Kevlar or fiberglass fabric and wound around a center dielectric core 52.  
5 Similarly the coil windings 51 are potted or encapsulated within the shell 53. Similarly the  
6 coil terminals 64 provide conductive mating surfaces to interface with the pulling gun 91  
7 shown in Fig. 1.

8           However, the coil windings 51 in stressing region 60 have been relieved from the  
9 lead-in regions 61, 61' by making them linear. This alters both the magnetic field 150 and  
10 the strength of the coil windings 51. The reason for doing this is the coil windings 51 in the  
11 central stressing region 60 for this type of coil 50 encounters forces like a bending beam with  
12 a pulling force in the center of the stressing region 60 counteracted with a push near the  
13 outside of the stressing region 60.

14           The goal is to perform work on the work piece 90 and not on the coil 50. With the  
15 perfectly cylindrical coil 70, the curved bending beam stretches and weakens itself, especially  
16 with tangential forces acting outwards on the edges of the coil windings 71. With the coil  
17 winding geometry 51, any inside tangential forces in the center of the stressing region 60 does  
18 not create the stress to stretch and deform the conductor material.

19           Cylindrical coil 50 also incorporates a clamp 58 to constrain and even place the coil  
20 windings 51 of the stressing region 60 into a preloaded compression. The outside clamp 58  
21 around the stressing region 60 constrains the coil windings 51 between center core 52 with  
22 screw 59. By tensioning screw 59 on coil base 55, the stressing region 60 is placed in  
23 compression. The center core 52 may be one piece incorporating the dielectric terminal 54

1 and the coil base 55. The center core 52, terminal 54, coil base 55, outside clamp 58, and  
2 outside shell 53 materials may be composite fiberglass, electrical grade phenolic, or similar  
3 material with sufficient electrical and mechanical properties. The screw 59 shown is  
4 nonmagnetic stainless steel but could also be other conductive or insulating materials.

5 To take advantage of clamp 58, the aperture 65 is altered from the prior art aperture  
6 85, shown in Fig. 2B & 2D. Instead of a tapered height, each coil winding 51 in the stressing  
7 region 60 is made the same height. This increases the magnetic field 130 produced in front  
8 of the stressing region 60 as a result of higher current concentration. Consequently, the  
9 higher magnetic field 130 improves the pulling efficiency of the coil windings 51. More  
10 importantly, each winding is completely captured by the clamp 58 to oppose the tangential  
11 forces resulting from the strong central magnetic field 130. Note that there are other methods  
12 of constraining or clamping the stressing region 60. A clamp 58 requires at least one  
13 component in tension. For example, the shell 53 could be used as the tension component if a  
14 wedge were driven in between to preload the stressing region 60.

15 Fig. 4A, 4B, and 4C shows the preferred embodiment of the invention, work coil 10.  
16 Work coil 10 is composed of similar basic coil components. The dipole conductive coil 10  
17 consists of layers of insulated windings 11, encapsulated within shell 13. The coil base 15  
18 and terminal dielectric 14 with conductive terminals 24 can be made interchangeable with  
19 prior art coils 70. Instead of a single center core, there are now two separate but identical  
20 clamp cores 18, 18'. Similar to clamp 58 in cylindrical coil 50, the clamp cores 18, 18' can  
21 be tensioned with screws 19 to preload the central linear stressing region 20 into  
22 compression. This is done by placing an interlocking wedge feature 17 on coil base 15 into  
23 compression with clamp cores 18, 18'.

1           The dipole coil 10 is now symmetric with a linear stressing region 20 in the center.  
2           Due to the dipole nature of the coil 10, the return path regions 22, 22' are split into two  
3           equivalent but separate areas, which further reduces the magnetic field there. The lead-in  
4           regions 21, 21' consists of tapered windings 11 that can vary in thickness between the  
5           stressing region 20 and the return path regions 22, 22'. The machined area 25 is similar in  
6           function to the aperture 65 and slot 67, which varies the height of the windings 11 between  
7           the stressing region 20 and the return path regions 22, 22'. Slot 88 in the return path winding  
8           region 82 of the cylindrical coil 70, as shown in Fig. 2B, 2D, is not necessary but could be  
9           implemented. Instead, coil 10 is shown with a slopped face 29, which helps decouple the  
10          return path regions 22, 22' from the work piece 90 at high frequency. The slopped face 29  
11          also has the advantage of increasing the preload pressure exerted by an operator locally over  
12          the stressing region 20 on the work piece 90.

13           It is beneficial to further increase the ratio of winding thickness between the stressing  
14          region 20 and the return path regions 22, 22', as shown in Fig. 5. The tapered lead-in region  
15          21 helps sink heat away from the stressing region 20. The resistance of the return path  
16          regions 22, 22' is kept low with greater conductive area and the corresponding magnetic field  
17          of the return path region 22, 22' is further reduced. With a higher winding density in the  
18          stressing region 20, the magnetic field is increased. That improves the efficiency of the coil  
19          10 and is limited only by the windings 11 in the stressing region 20 being capable of  
20          withstanding the stressing forces. The goal is to do work on the work piece 90 and NOT on  
21          the coil 10.

22           As we further increase the ratio of winding thickness between the stressing region 20  
23          and the return path region 22, 22', or with use of harder conductor materials that are not

1 easily formed into complex geometry, we become increasingly reliant on a method of  
2 manufacture using wire EDM. To use this method, first the machined area 25, the slopped  
3 face 29, and the pockets for the clamp core 18 are CNC milled from a solid block of  
4 conductor material. Side access holes for screws 19 are drilled. The wire EDM is started  
5 from each clamp core 18, 18' pocket to cut a single winding at a time in a spiral fashion from  
6 the inside out. The outer shape and final winding is cut last to release the coil windings' 11  
7 from the block. A non-conductive shelf is made for the wire EDM machine lower arm so  
8 that as the windings 11 are cut they rest freely and slide on the table. One parameter and  
9 drawback of wire EDM that has to be controlled or accounted for is the heat effected zone of  
10 the cut where the material is burned away and may even be redeposited leaving a thin layer of  
11 weak softened material on the walls of the windings 11. This may be compensated for and  
12 cleaned up by etching the windings 11 in acid.

13 After the windings 11 are cut via wire EDM they are flexible like a spring. Shown in  
14 Fig. 6A, this makes it easier to hand wind dielectric insulation 30 around windings 11. Many  
15 fabrics and dielectric materials can be used for dielectric insulation 30. Kevlar provides the  
16 best excellent mechanical strength but thin materials like polyimide film may also be used to  
17 help thermally insulate the hot windings 11 and provide excellent dielectric 30. The wire  
18 EDM cut width through the stressing region 20 can be made wider than the desired final  
19 dielectric thickness. The coil 10 is flexible like a spring so the final dimensions of the  
20 resulting stressing region 20 is a simple function of leftover conductor material and applied  
21 dielectric thickness. While it is important to have even coverage of dielectric 31 on every  
22 winding in the stressing region 20, it is less of a requirement in the return path region 22.  
23 After the coil 10 is clamped together on coil base 15, as shown in Fig. 4C, and fitted inside